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Utility of a Dual-Lidar Method to Measure Integrated Extinction

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This report considers a proposal for a dual-lidar method to directly measure atmospheric extinction and backscatter coefficient profiles without the need to make the usual assumptions of horizontal homogeneity or constant backscatter-to-extinction ratio. A complete mathematical derivation for both techniques is presented. A dual-lidar method for measuring optical depths is demonstrated, but while the theory is valid, evaluating the accuracy of the results is difficult.

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INTRODUCTION

A dual-lidar method has been proposed as a way to measure atmospheric extinction and backscatter coefficient profiles without the need to make the usual assumptions of horizontal homogeneity or constant backscatter-to-extinction ratio (Paulson, 1987; Hughes & Paulson, 1988). While the technique is valid in theory, at least for spherical aerosols, its application may be quite difficult. This is particularly true when trying to use the existing equipment.

A similar dual-lidar method has been proposed to directly measure integrated extinction, or optical depth, over a path between the two lidars without the need to know the slope of the curve along the path. This is the technique that will be considered here. A complete mathematical derivation for both techniques will be presented, however, since they are related.

MATHEMATICAL DERIVATIONS

EXTINCTION COEFFICIENT PROFILES

The quantity S(R) is the natural logarithm of the product of the backscattered power received from range R and R^2. If the two lidars are separated a distance d, as shown in figure 1, and the origin is at lidar 1, the equation for S(R) for the first lidar is

$$S_1(R) = Ln(C_{11}) + Ln[\beta(R)] - 2\int_0^R \sigma(r)dr \tag{1}$$

and that for the second lidar is

$$S_2(R) = Ln(C_{12}) + Ln[\beta(R)] - 2\int_R^d \sigma(r)dr \tag{2}$$

where C_{11} and C_{12} are the instrumentation constants for each of the lidars. Sigma(r) is the extinction coefficient at range r, and $\beta(R)$ is the backscatter coefficient at range R.

If equation 2 is subtracted from equation 1, we get

$$S_1(R) - S_2(R) = Ln(C_{11}) - Ln(C_{12}) - 2\int_0^R \sigma(r)dr + 2\int_R^d \sigma(r)dr \ . \tag{3}$$

Since

$$\int_R^d \sigma(r)dr = \int_0^d \sigma(r)dr - \int_0^R \sigma(r)dr \ , \tag{4}$$

equation 3 becomes

$$S_1(R) - S_2(R) = Ln(C_{11}) - Ln(C_{12}) - 4\int_0^R \sigma(r)dr + 2\int_0^d \sigma(r)dr \ . \tag{5}$$

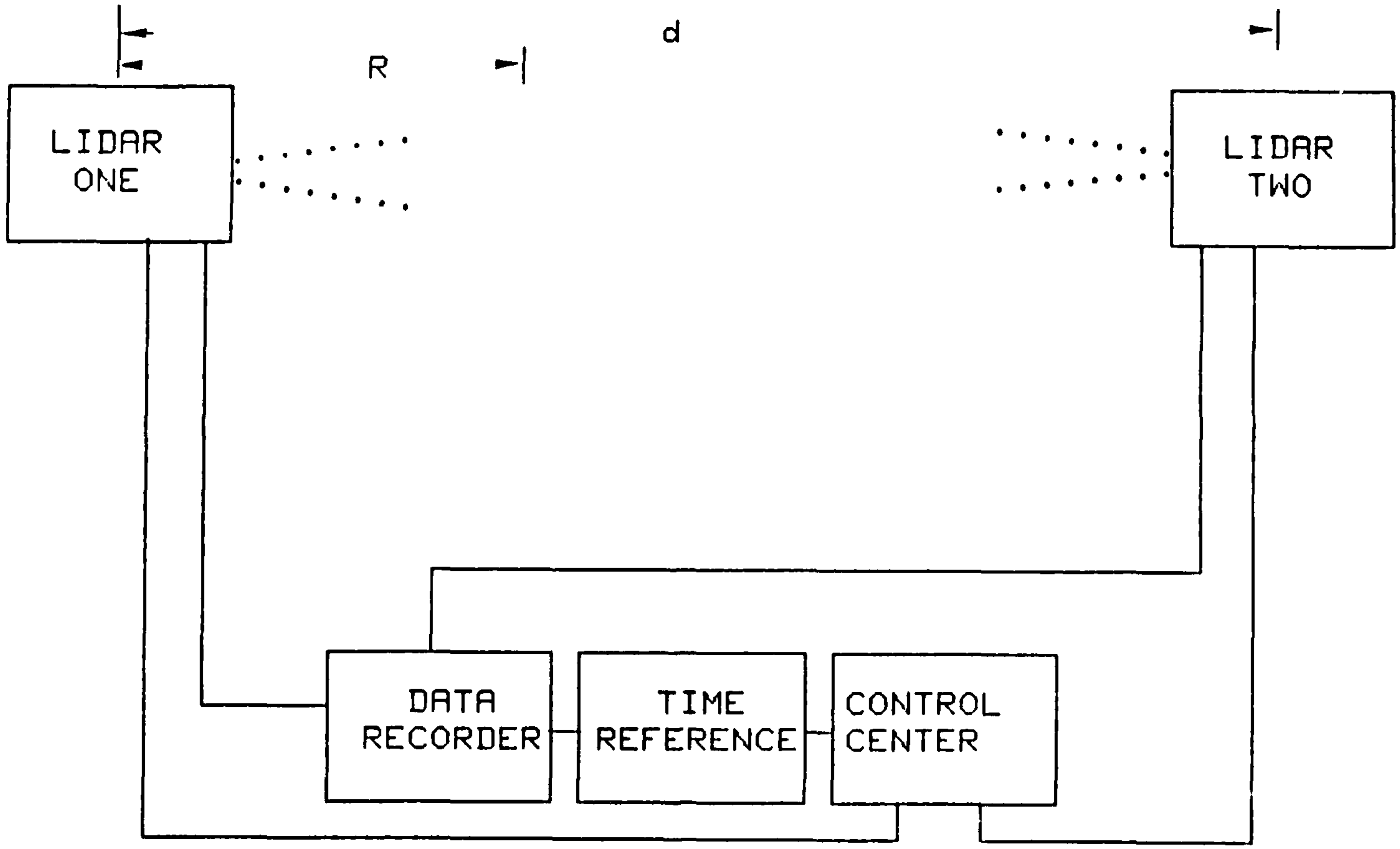


Figure 1. Block diagram of a possible dual-lidar system for measuring atmospheric extinction and backscatter coefficient profiles and optical depth.

Taking the difference between equations 1 and 2 eliminates the backscatter coefficient. Taking the derivative of equation 5 eliminates the requirement that constants C_{11} and C_{12} be known and we get

$$dS_1(R) - dS_2(R) = -4\sigma(R)dR \tag{6}$$

or

$$\sigma(R) = \frac{\frac{dS_2(R)}{dR} - \frac{dS_1(R)}{dR}}{4} \quad . \tag{7}$$

The calibration curves for each of the lidar receivers are still needed, however, and must be accurately known since they affect the slope characteristics of the S(R) curves. Since the propagation for the two lidars is in opposite directions with respect to the origin, the slopes of $S_1(R)$ and $S_2(R)$ should have opposite signs under homogeneous conditions.

INTEGRATED EXTINCTION AND VISIBILITY

While integrated extinction can be obtained by integrating the extinction coefficient profile, it can be obtained more directly. If equation 3 is written for two different distances, R_1 and R_2, we get

$$S_1(R_1) - S_2(R_1) = Ln(C_{11}) - Ln(C_{12}) - 4\int_0^{R_1} \sigma(d)dr + 2\int_0^{d} \sigma(r)dr \tag{8}$$

and

$$S_1(R_2) - S_2(R_2) = Ln(C_{11}) - Ln(C_{12}) - 4\int_0^{R_2} \sigma(d)dr + 2\int_0^{d} \sigma(r)dr \quad . \tag{9}$$

Subtracting equation 9 from equation 8 gives

$$[S_1(R_1) - S_2(R_1)] - [S_1(R_2) - S_2(R_2)] = -4\int_0^{R_1} \sigma(r)dr + 4\int_0^{R_2} \sigma(r)dr \quad . \tag{10}$$

Using the following equation

$$\int_{R_1}^{R_2} \sigma(r)dr = \int_0^{R_2} \sigma(r)dr - \int_0^{R_1} \sigma(r)dr \ , \tag{11}$$

we get

$$\int_{R^1}^{R_2} \sigma(r)dr = \frac{[S_1(R_1) - S_2(R_2)] - [S_1(R_2) - S_2(R_2)]}{4} \tag{12}$$

Again, the instrumentation constants drop out.

If atmospheric conditions were homogeneous, this could be used to calculate visibility with use of the equation

$$\mathrm{Vis} = \frac{3.912\ (R_2 - R_1)}{\int_{R_1}^{R_2} \sigma(r)\,dr} \tag{13}$$

which is the Koschmieder relationship with the extinction coefficient replaced by an average extinction coefficient over the interval R_1 to R_2.

REQUIREMENTS FOR ACCURATE RESULTS

For the technique to give accurate results, several things are required. In particular, both lidars must be accurately calibrated over the total range of their gain curve. When the extinction becomes low, the S(R) difference curve tends to go horizontal, and if the calibrations are not very accurate, even small errors in the calibration can result in a large percent of errors in the measured extinction. The apparent extinction could even go negative sometimes.

The lidars must also see essentially the same atmospheric irregularities. For this to occur they must be aligned carefully along the same path, but in opposite directions. Also, they must be fired at very nearly the same instant.

In cases where there are large abrupt changes in the backscattered signal intensity, it is necessary to have a measurement of the separation distance between the lidars that is better than one range cell; in the case of the visioceilometers, that is 7.5 meters. Even then some data smoothing is required.

Because of the narrow field of view of the lidars, small irregularities can look somewhat different to the two lidars. The lidar transmitter has a 1-milliradian field of illumination. If the lidar happened to be pointed just right, an irregularity at 100 meters with a diameter of about 10 cm could intercept almost all of the energy from the lidar pulse. The same 10-cm irregularity at, say, 800 meters for the other lidar would encounter, at the most, 1 to 2 percent of its energy.

In the case of extinction coefficient profiles, in order to get a measurable slope of the S(R) difference curve some finite range increment is required. How large this increment needs to be will depend on several things. One of these is the signal-to-noise ratios for the two lidars. Another is the digital resolution of the digitizers. These become particularly critical in regions and/or conditions of low extinction.

While these requirements are particularly important for getting measured extinction and backscatter profiles, they are important for getting integrated extinction measurements as well. They are probably not quite as critical, however, except in cases of high visibility and low extinction.

LIDAR CALIBRATIONS

Lidar #025091, (2), was calibrated in March 1986 with the assistance of personnel at the Physics and Electronics Laboratory, TNO in The Netherlands (Ferguson & Paulson, 1986). Additional calibrations were made on this lidar and on lidar #025090, (1), in 1988. A least-squares fit to a straight line was calculated for decibels of signal input versus voltage out for each lidar. This provided a calibration constant of decibels per volt, or volts per decibel, for each lidar. Several calibrations showed that variation in this constant from calibration to calibration was usually less than ±5 percent.

These calibration constants were used with the dual-lidar technique to calculate optical depths for a series of shots on 9 March 1988. The constants were then increased by 5 percent for both lidars and the calculations were repeated. Next the constants were decreased 5 percent below the calculated values and optical depths were recalculated. The results are shown in figure 2. It appears that a 5-percent error in the calibration constants causes a constant offset in the optical depth above and below that calculated with use of the measured calibration constants. This would say that the larger the optical depth measured, the less percent error introduced by a given error in the calibration constants. Figure 3 shows a plot of percent error in optical depth, caused by a 5-percent error in calibration constant, versus optical depth for these data. This curve would suggest that, under these conditions, to get no more than ±20-percent error in measured optical depth, the measured optical depth would have to be 0.4 or greater.

Although the use of the slope of an S(R) curve to calculate an extinction coefficient is generally considered not valid, it is of interest to see what effect errors in calibration might have on the results if this method is used. A sequence of horizontal shots made on 15 October 1987 with lidar 2 was used to test this. A least-squares fit to a straight line for data between 0.12 and 0.5 km was used to calculate a nominal extinction coefficient. Calibration constants of 5 percent above and then 5 percent below the measured value were used and the process was repeated for each case. The results are plotted in figure 4. Here again there appears to be a fixed offset above and below the nominally correct values. When this is considered as percent error as a function of extinction coefficient, plotted in figure 5, it appears that, if there were no other sources of error, for errors resulting from a 5-percent error in calibration to produce less than 20-percent error in extinction coefficient, the extinction coefficient measurement would have to be greater than 0.9. That is a result of calibration error only. Other things, such as lack of horizontal homogeneity, would produce additional errors.

Subsequent to the 1988 calibration measurements, it was concluded that a linear fit to the calibration data was not adequate. For this reason, a fifth-order fit to the curve was calculated for each of the lidars. These are shown in figure 6 for lidar 1 and in figure 7 for lidar 2.

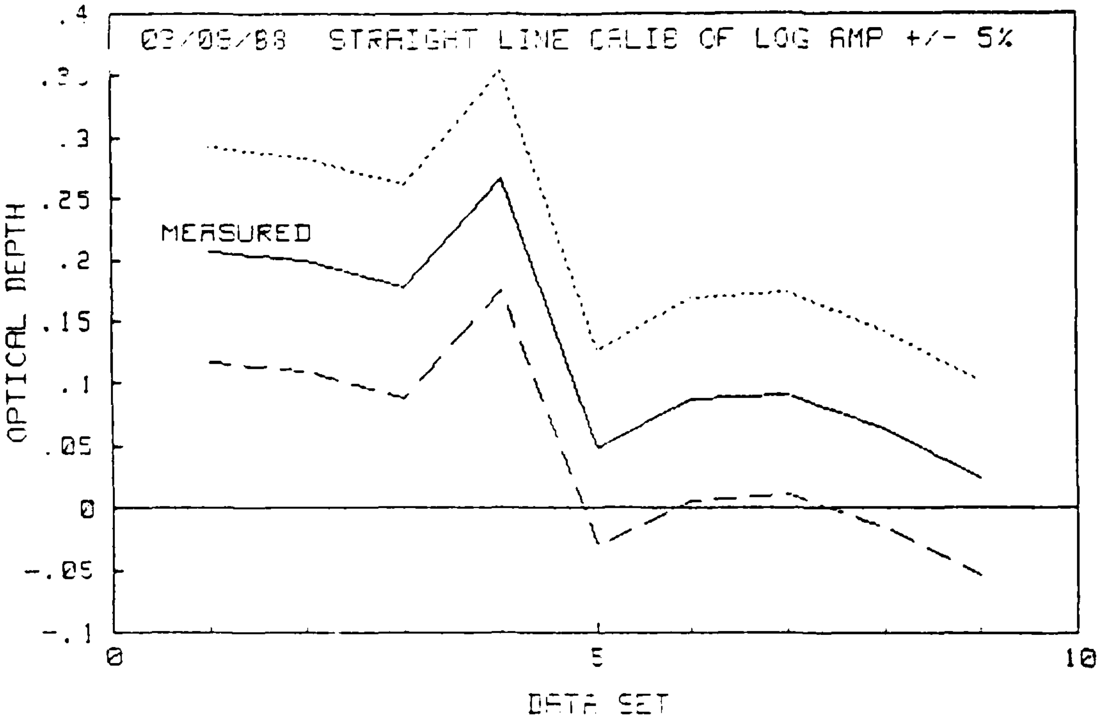


Figure 2. Effects of ±5-percent error in log amplifier calibration on optical depth measurements.

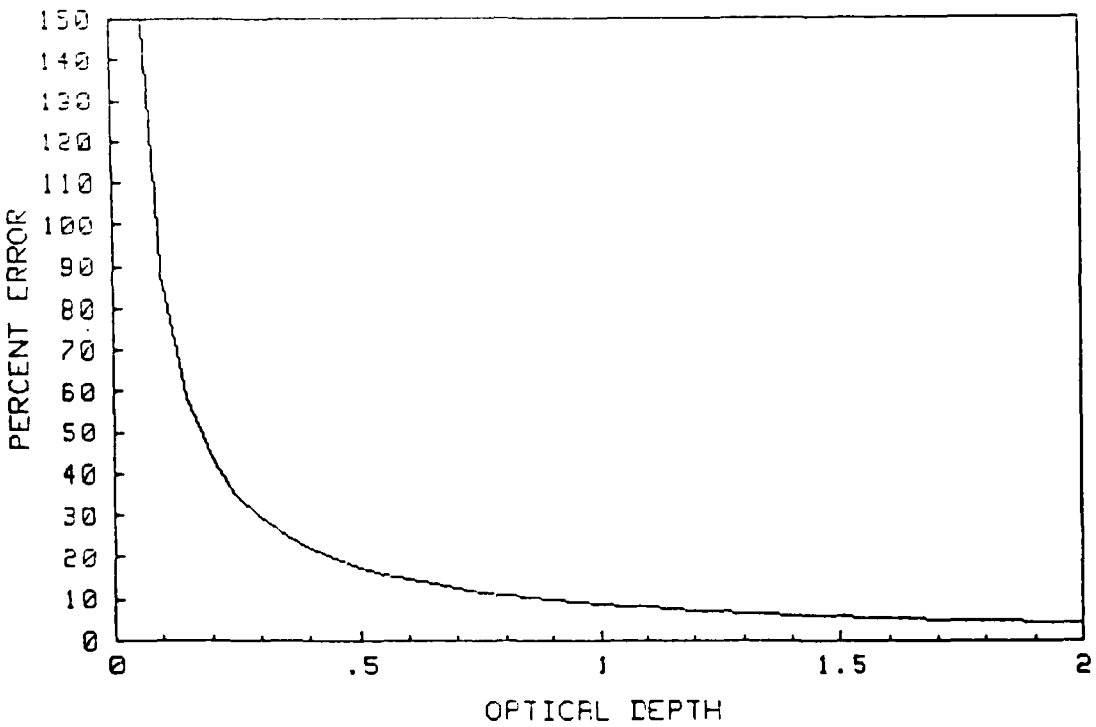


Figure 3. Percent error in optical depth as a function of optical depth for a log amplifier calibration error of ±5 percent.

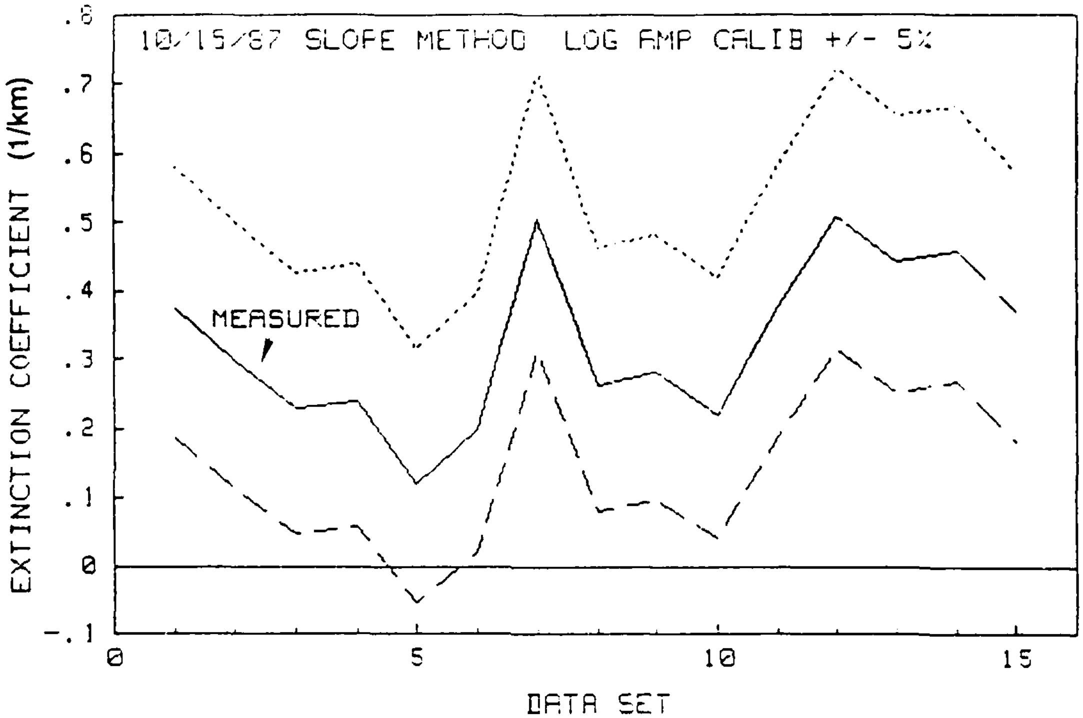


Figure 4. Effects of $\pm$5-percent error in log amplifier calibration on the nominal extinction coefficient calculated by the slope method.

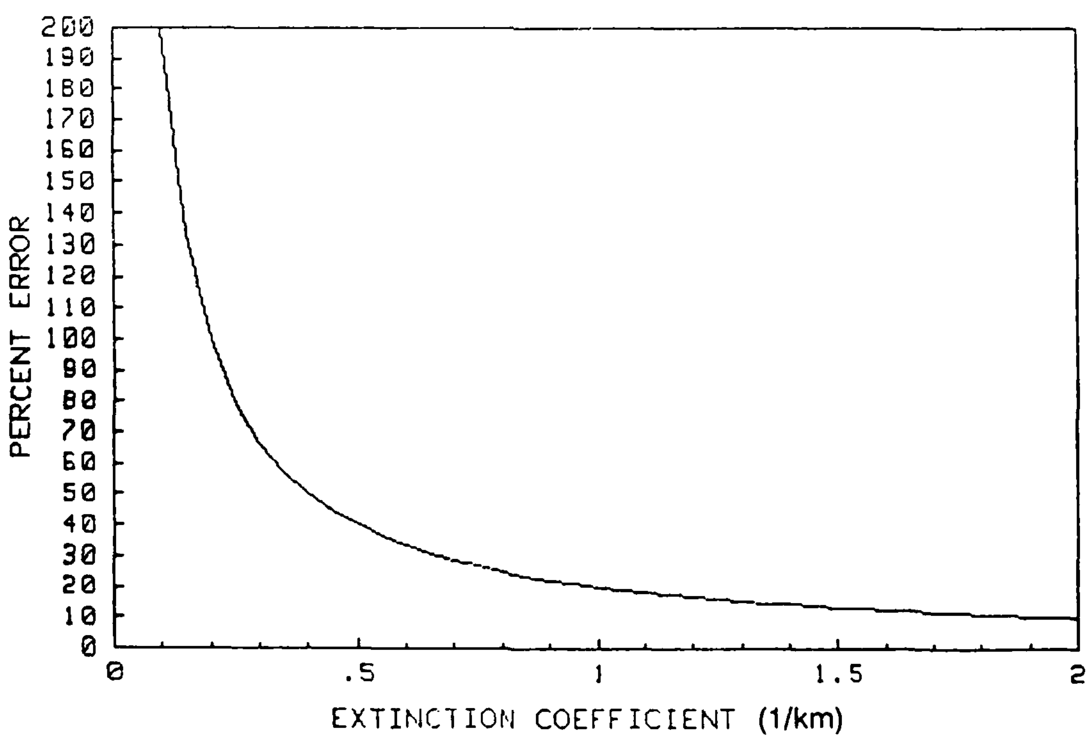


Figure 5. Percent error in nominal extinction coefficient as a function of extinction coefficient for a log amplifier calibration error of $\pm$5 percent.

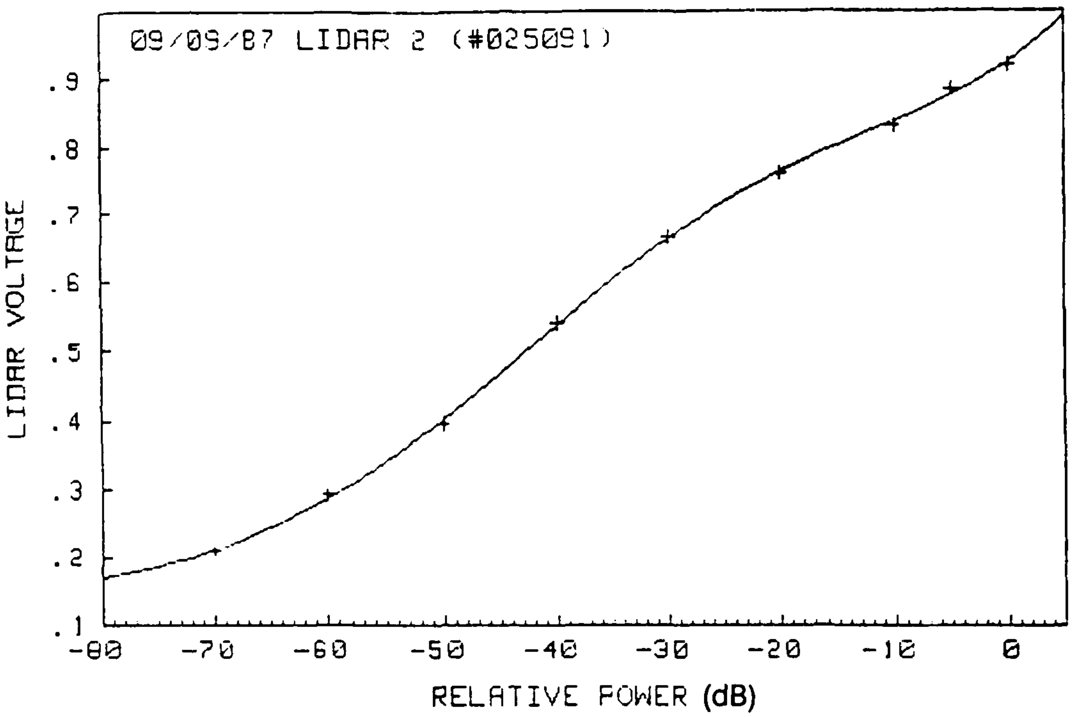


Figure 6. Fifth-order fit to calibration data for lidar #025091.

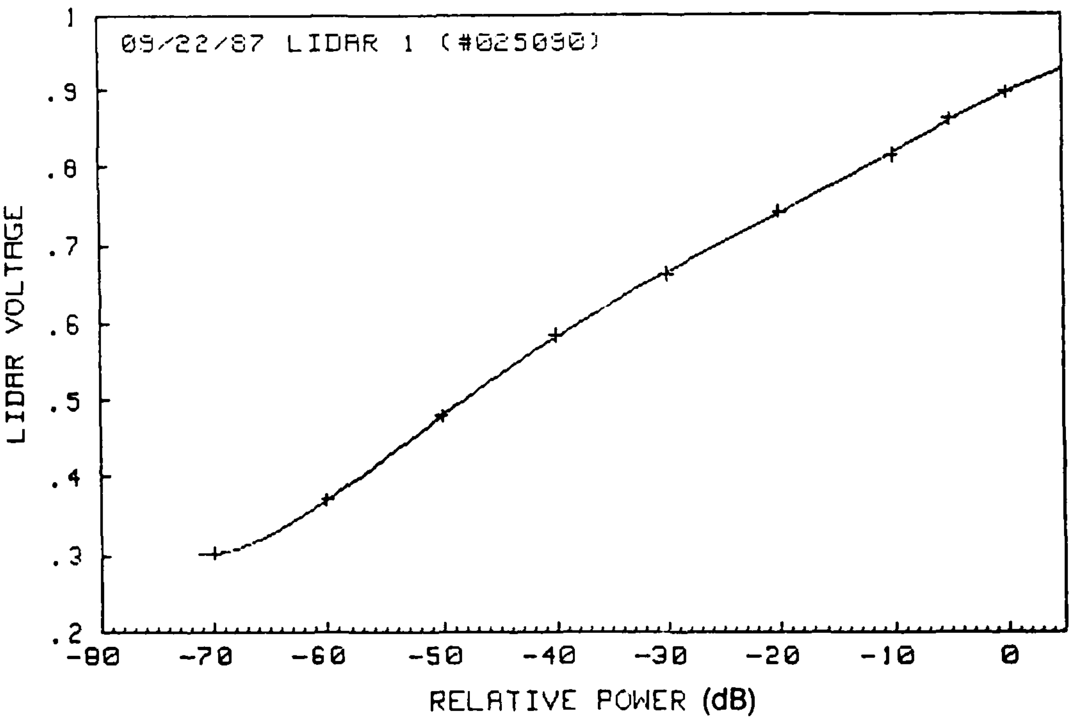


Figure 7. Fifth-order fit to calibration data for lidar #025090.

MEASUREMENT PROCEDURE

Two propagation paths were used for these measurements. The first was between building 323 and building 593, with building 323 considered the origin, or range zero. Building 323 is on Point Loma at about 30 to 35 meters above the Pacific Ocean. Building 593 is southeast of building 323 at a range of 0.9825 km and 130 to 135 meters above the ocean.

The second propagation path was between building 323 and a van to the north at a range of 0.57 km, with the van considered the origin, or range zero. In this case lidar 1, at the van, was on a tripod near ground level, while lidar 2, at building 323, was in a radome on top of the building. This put lidar 2 about 10 meters higher than lidar 1.

A series of 10 or more shots was usually made with a repetition time interval somewhere between 1/2 and 1 minute. Firing of the two lidars was coordinated over a radio link to insure that the two lidars were fired within about 1 second of each other. Figure 8 shows an example of the S(R) curves with the corresponding S(R) difference curve.

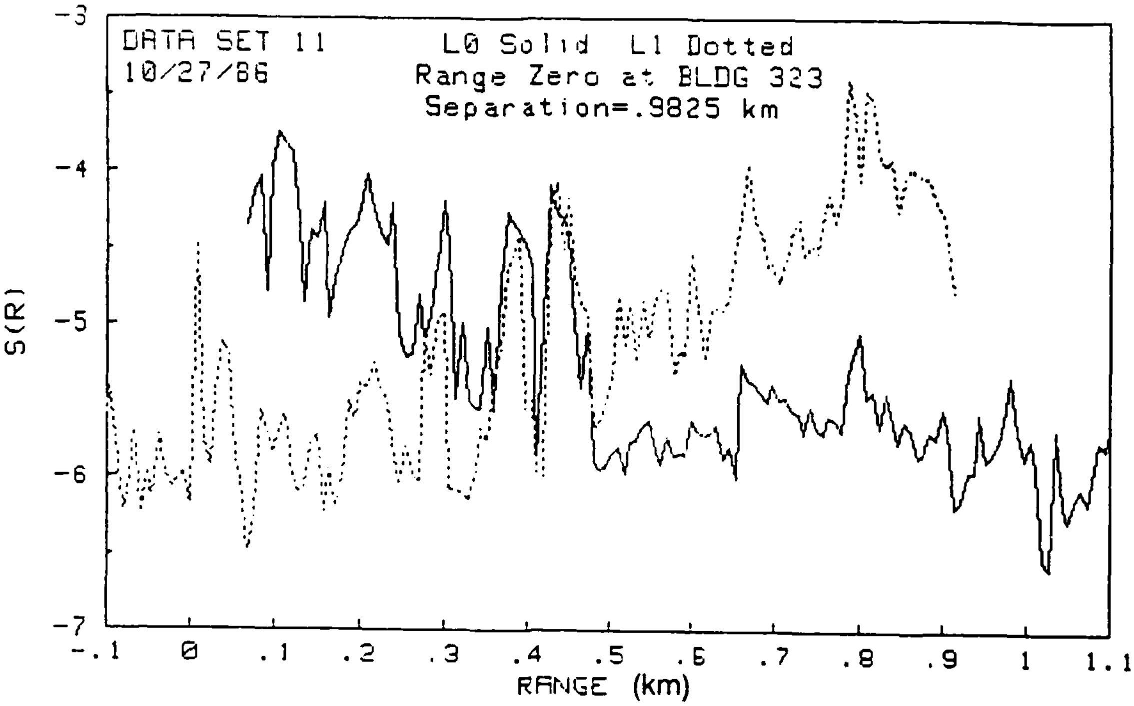
DATA ANALYSIS

DATA AVERAGING

Because aerosol irregularities with very small dimensions are regularly observed, it is necessary to do some *data averaging*, or smoothing, to get consistent results. This is particularly so for conditions of good visibilities, or low optical depths. Running averages of 3, 5, and 11 data points were used, as well as no averaging, and the resulting S(R) difference curves were compared. Figure 9 shows an example of these for no averaging and running averages of 3, 5 and 11 for the same data sample.

These averages were used for all of the data samples. The 11-point averages were used as a reference, and the percent difference between it and the 5, 3, and no average cases was calculated. These are tabulated in table 1. These results do not provide much in the way of quantitative evaluation of the various running averages. It appears, though, that running averages of about 11 provide reasonably consistent results. In the cases of the higher visibilities, three of the measurements went slightly negative on 10 February and one on 24 February.

In order to evaluate the accuracy of the dual-lidar technique, it is necessary to have some other method of measurement, the results of which can be considered correct and accurate, with which these results can be compared. There has not been much success, so far, in finding such a reference. At one time it was planned to compare the results to those of a Knollenberg Spectrometer, but this was cancelled. There was some question as to which would be considered the reference. Of course it could be of interest if both methods gave similar results.



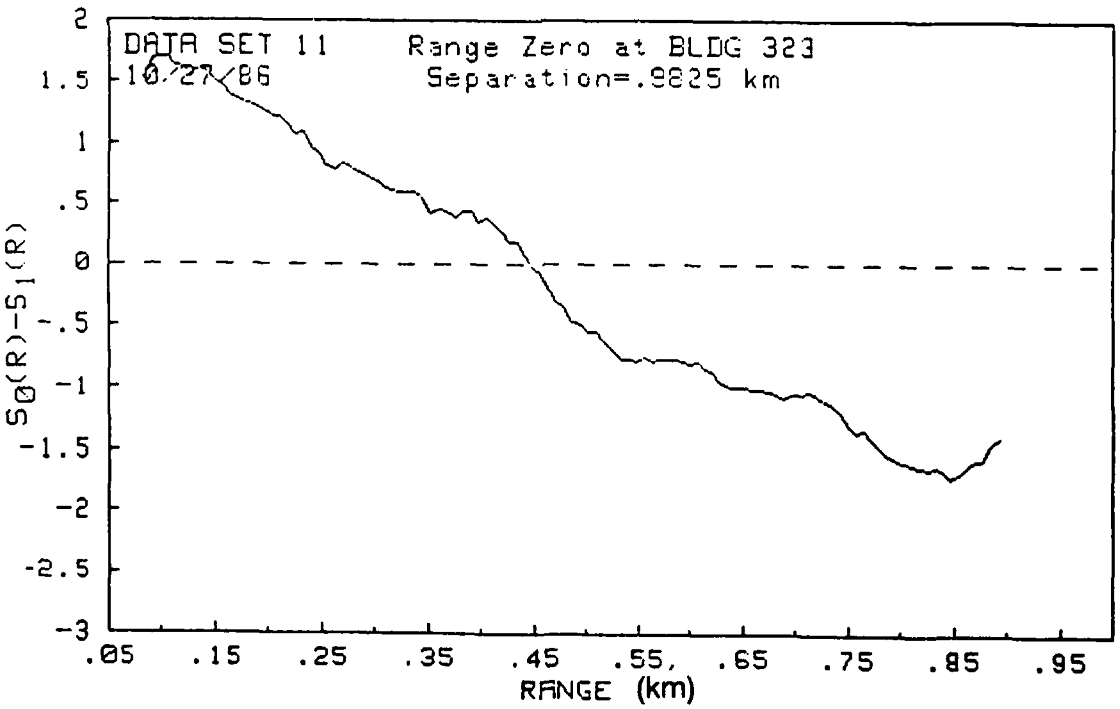
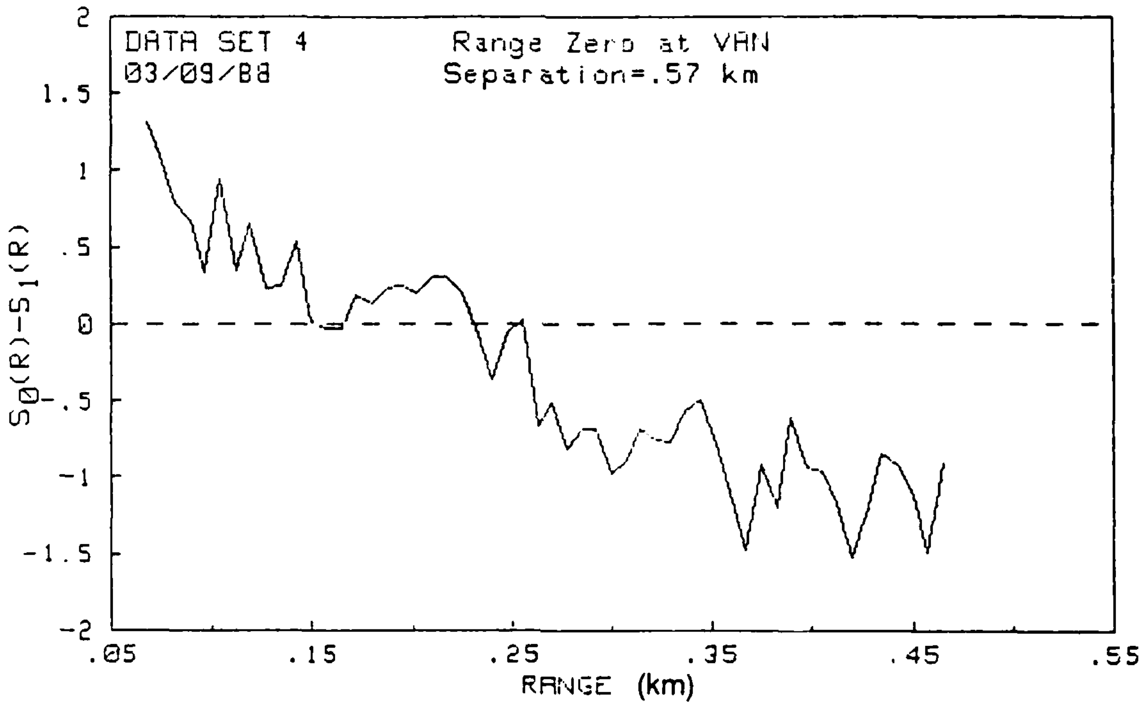
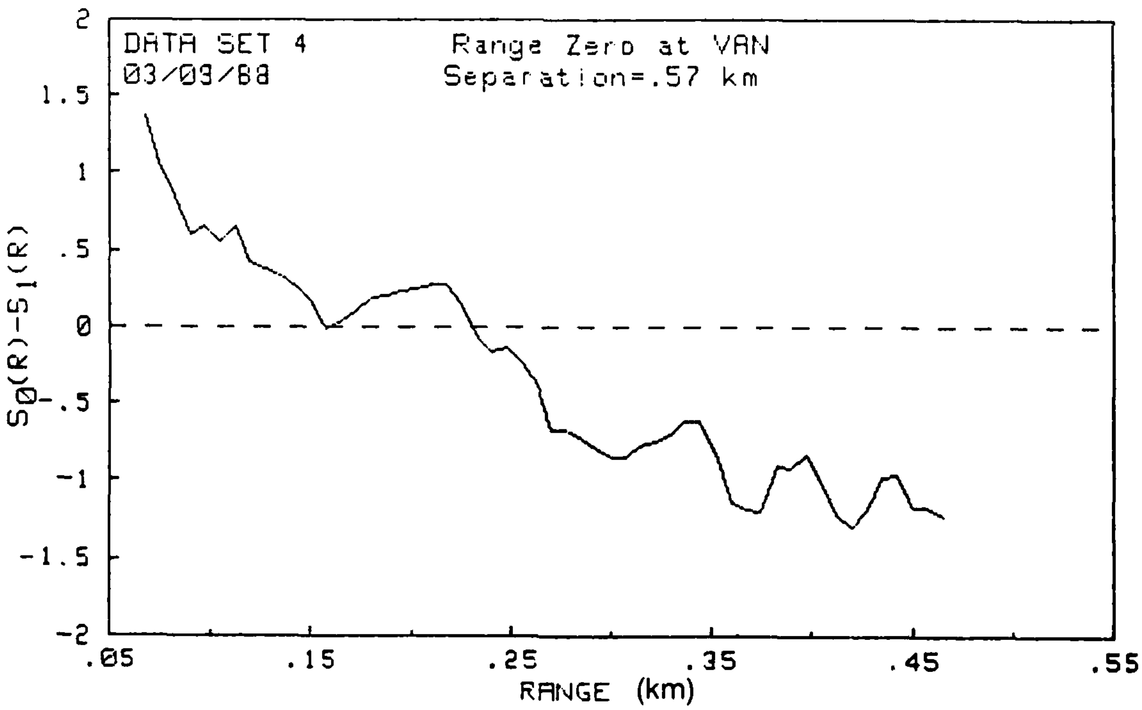


Figure 8. Upper graph is an example of S(R) data obtained with the dual-lidar technique. Lower graph is an 11-point running average for the S(R) difference curve for these data.

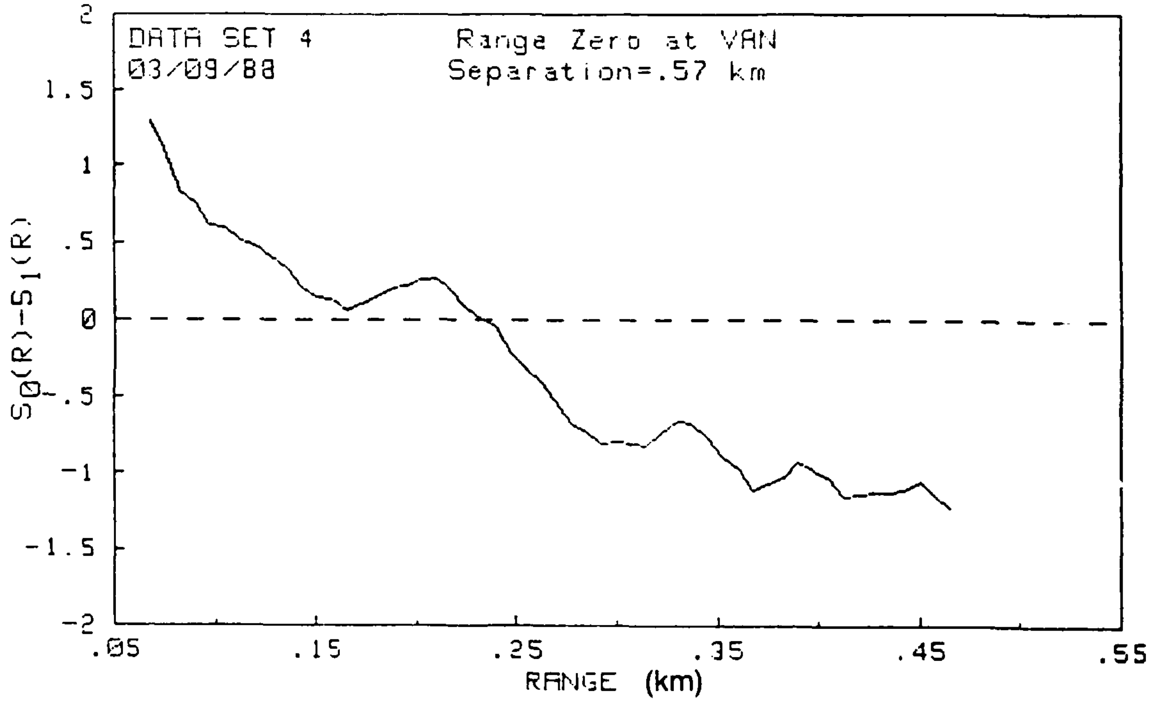


(a)



(b)

Figure 9. An example of S(R) difference curves showing (a) no averaging, (b) 3-point running average, (c) 5-point running average, and (d) 11-point running average.



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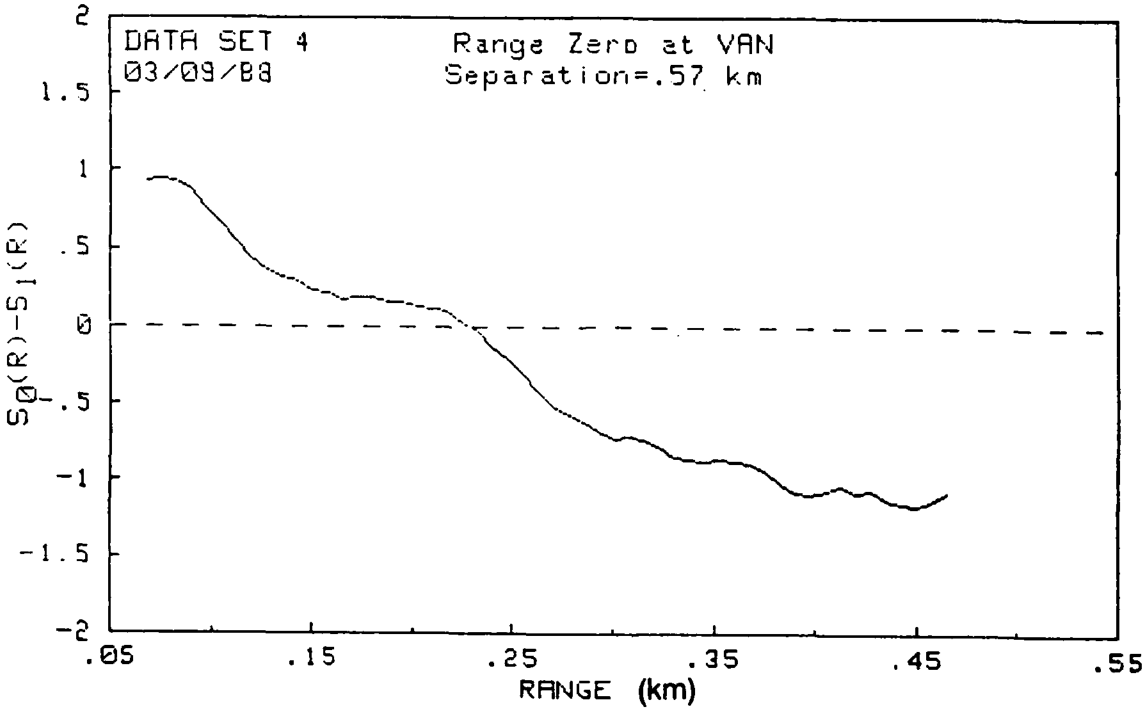

(d)

Figure 9. An example of S(R) difference curves showing (a) no averaging, (b) 3-point running average, (c) 5-point running average, and (d) 11-point running average (cont.).

Table 1. Optical depth calculations are given for 11-point running averages. No averaging and running averages of 3 and 5 are shown as percent differences from the 11-point values.

DATE 10/27/86		AVERAGES		
DATA SET	OD(11)	0	3	5
2	0.6773	4.9	5.0	-0.0
3	0.5069	-6.3	-11.0	-2.8
4	0.3896	27.3	13.5	5.3
5	0.4077	-12.6	-7.9	-1.8
6	0.5447	38.4	16.0	11.8
7	0.4297	-34.4	-21.8	-20.4
8	0.5277	-36.4	-16.4	-7.8
9	0.6698	-16.8	-0.7	-2.4
10	0.9044	4.6	1.9	5.6
11	0.8064	-26.0	-8.8	-5.2
12	0.7329	39.5	17.4	12.3
DATE 10/30/86		AVERAGES		
DATA SET	OD(11)	0	3	5
1	0.3132	-21.7	11.4	4.3
2	0.3003	31.1	32.1	9.8
3	0.2789	1.6	10.4	18.3
4	0.2940	-7.2	-10.9	-3.6
5	0.3555	-7.4	-0.5	2.8
6	0.3206	-4.5	-4.2	0.5
7	0.2950	8.4	1.4	6.4
8	0.2907	3.3	1.4	4.3
9	0.2208	-0.8	14.3	5.2
10	0.3107	4.2	-4.6	-12.0
DATE 02/09/88		AVERAGES		
DATA SET	OD(11)	0	3	5
1	0.3480	-15.7	-21.2	-14.4
2	0.2711	-20.7	-13.0	-9.0
3	0.0260	-137.5	-29.2	182.4
4	0.1418	-68.7	-60.3	-37.8
6	0.1931	-31.2	-37.5	-29.2
7	0.2302	78.4	58.1	25.0
8	0.1499	-7.9	-3.4	-11.7
9	0.3428	-23.4	-6.0	-2.3

Table 1. Optical depth calculations are given for 11-point running averages. No averaging and running averages of 3 and 5 are shown as percent differences from the 11-point values (cont.).

DATE 02/10/88		AVERAGES		
DATA SET	OD(11)	0	3	5
2	-0.0003	-197.7	-214.5	-186.7
3	0.0033	-221.0	-177.6	-155.8
4	0.0689	6.4	14.5	1.9
5	0.1174	-45.9	-26.2	-26.6
6	0.0327	143.3	10.6	25.5
7	0.0191	-28.3	-39.8	-35.3
8	0.0408	-35.2	-14.4	-21.1
9	-0.0681	-53.9	5.0	-10.3
10	-0.0764	17.1	-9.6	-12.5

DATE 02/23/88		AVERAGES		
DATA SET	OD(11)	0	3	5
1	0.1187	43.9	52.2	35.5
2	0.0076	-157.4	-464.4	-390.0
3	0.1245	-18.0	2.0	-7.7
4	0.1048	-59.2	-1.1	-26.1
5	0.1050	-76.1	-49.4	-9.8
6	0.1123	14.3	-6.6	-10.7
7	0.1044	-29.8	1.7	6.7
8	0.1252	-0.2	16.4	6.9
9	0.1133	65.6	72.8	69.4

DATE 02/24/88		AVERAGES		
DATA SET	OD(11)	0	3	5
1	0.0645	-62.7	-53.2	-47.0
2	-0.0750	90.4	28.9	30.9
3	0.3499	-24.6	-14.9	-13.8
4	0.1180	82.1	54.7	26.8
5	0.0719	-28.1	19.4	31.6

DATE 03/09/88		AVERAGES		
DATA SET	OD(11)	0	3	5
1	0.3214	32.8	6.8	19.3
2	0.3342	1.6	-5.3	3.8
3	0.3177	-0.8	-5.0	-3.3
4	0.4263	14.9	-7.0	8.9
5	0.1321	18.6	0.4	-0.9
7	0.2288	-3.6	-26.0	-17.4
8	0.2219	-52.3	-27.3	-3.6
9	0.1864	-60.8	-40.1	-35.8
10	0.1499	-23.1	-15.9	-16.3
12	0.1855	-54.9	-28.5	-16.2
13	0.2522	-22.8	-19.6	-18.4
14	0.0562	-745.6	2.3	31.3
15	0.1698	27.5	8.0	0.2

SUMMARY

A dual-lidar method for measuring optical depths has been demonstrated. While the theory is valid, evaluating the accuracy of the results is very difficult. In order to do this, an independent and accurate method of measuring optical depth is needed that can be used as a reference. Such a reference has not yet been found.

When visibility was high, the measured optical depth went slightly negative on three or four occasions. This was probably caused by small variations in the gain of the lidar's logarithmic amplifiers. Repeated calibrations of the lidars showed the calibrations to vary by less than ±5 percent. For this sort of variation to cause a less than ±20-percent error in the measured optical depth, the optical depth would need to be greater than 0.4.

Some data smoothing is needed because of very small-scale irregularities which are not seen exactly the same by both lidars. It appears that a running average of about 11 data points will provide the necessary smoothing in most cases.

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